GUST MEASUREMENTS ON CONCORDE

R. Dieudonné

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16. Abstract

2/75 scale models of wing, wing and fuselage and complete SST Concorde models have been tested for gust effects on trajectory, velocity and acceleration for free flight conditions. The trajectory measures 20 chords and the gust is simulated with blowers. Experimental results are compared with calculations of stall conditions and suggestions for improvement are given.

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CHAPTER I

Series of Experiments

We will briefly recall the methods, the models, and the equipment utilized during these tests. /I-01*

1.1. General Remarks on the Experimental Method

The tests consist in implementing specific free model flights during the course of which the phenomenon of wind gusts is created by a wind tunnel.

Information relating to the flight is collected either by airborne sensors connected to a system of radio telemetry, or by means of ground equipment.

The test models are defined by the similitude of Froude with a length scale λ^{-1}, mass scale λ^{-3}, inertia scale λ^{-5}, velocity and time scales $\lambda^{-1/2}$, linear and angular accelerations 1 and λ, etc.

Moreover, this similitude can be more or less complete, and the comparison calculations are realized for the model itself.

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*Numbers in the margin indicate pagination in the original foreign text.

1.2. Models

The models have been conceived to represent three principal configurations: wing only, wing and fuselage, and complete aircraft with thrustor nacelles.

The scale chosen λ^{-1} is 2/75.

The airfoil only carries, however, a pseudo-fuselage of reduced dimensions, permitting the installation of the fin similar to the aircraft and the implantation of measuring equipment.

The model wing-fuselage is homologous to the aircraft in the cruising configuration for the forward fuselage. /I-02

For the case of the complete model, the whole aircraft is represented with permeable engine nacelles with two-dimensional cross sections along its entire length.

We can see the three types studied on Plate I.01.

The resistant structure of the airfoil is entirely metallic, and the understructure is made of resin or balsa wood.

These models must represent a rigid aircraft. In fact, the first harmonics have a frequency on the order of 50 Hz for a fundamental gust frequency in the neighborhood of 8 Hz. Besides, for these harmonics, the presence of two node lines means that a privileged position for the implantation of accelerometers exists.

1.3. Test Equipment

The purpose of this equipment is to measure trajectory, velocity, and acceleration.

The trajectories are obtained by the restitution of a chronological photography of luminous spots defining a reference axis of the model during the flights.

The velocities are computed with the help of a system of optical barriers arranged along the trajectory and triggered by a directed spot beam carried by the model.

Acceleration measurements are made by linear accelerometers placed at the two points of the axis of symmetry. Information furnished by the two sensors and transmitted by two remote analog control links allow the determination of the dynamic behavior characterized by the normal acceleration z'' at the center of mass, and the angular pitch acceleration θ''.

The performance of the equipment utilized at that time can be given with the following rough accuracy:

— trajectory Δz approximately 3 to 6% of the maximum measurement;

$\Delta\theta$ approximately 5 - 10% of the maximum measurement;

— kinematic ΔV 5/10,000;

— accelerometer effect $\Delta z''$ about 5 to 10%.

We can, nevertheless, note that the cross checks obtained by /I-03 double integrations of the accelerometer data, compared to the geometric flight data, allow us to correct the deviations from zero of a series of measurement and to validate the results retained as valid for the different tests with an accuracy superior to the coarse accuracies.

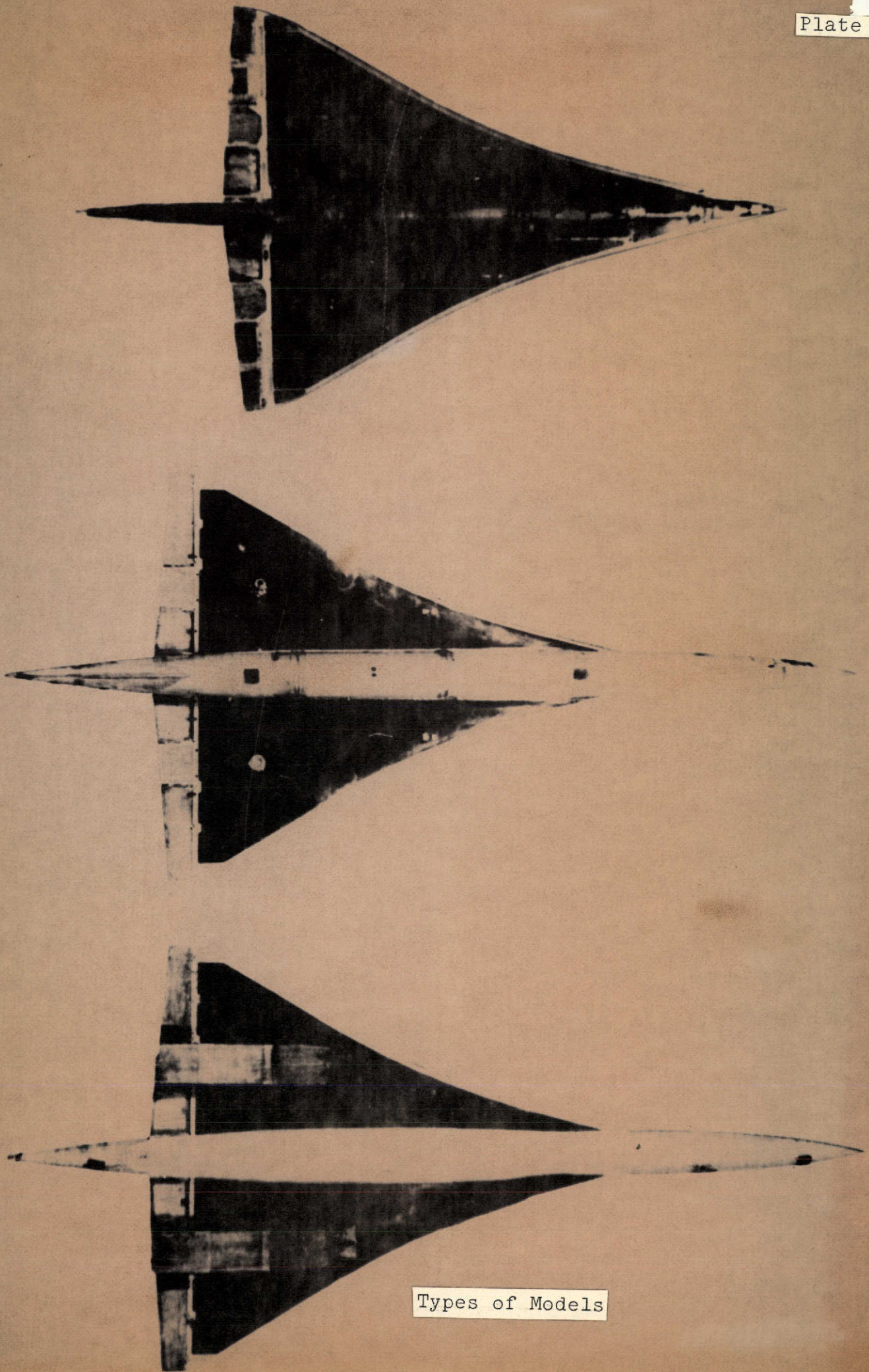
1.4. Ground Equipment

The study was carried out in the gust test station of the I.M.F. of Lille at the beginning of its operation.

The models are set in free flight by a catapulting device consisting of a ramp, a propulsion sled and an acceleration unit.

The powered run is approximately 20 chords in length, followed by free flight of 15 chords in quiescent atmosphere for the purpose of damping parasitic perturbations due to the catapulting. Passage through a gust then follows. Its wavelength for these tests has been fixed at 4 reference chords, but a frequency sweep is possible in free flight for approximately 10 chords following the gust and before the interception of the model.

A blower with a return and with an open jet generates the gust traversed by the model. The form of the gust is obtained with a high degree of accuracy. A schematic of the installation is presented on Plate I.02.

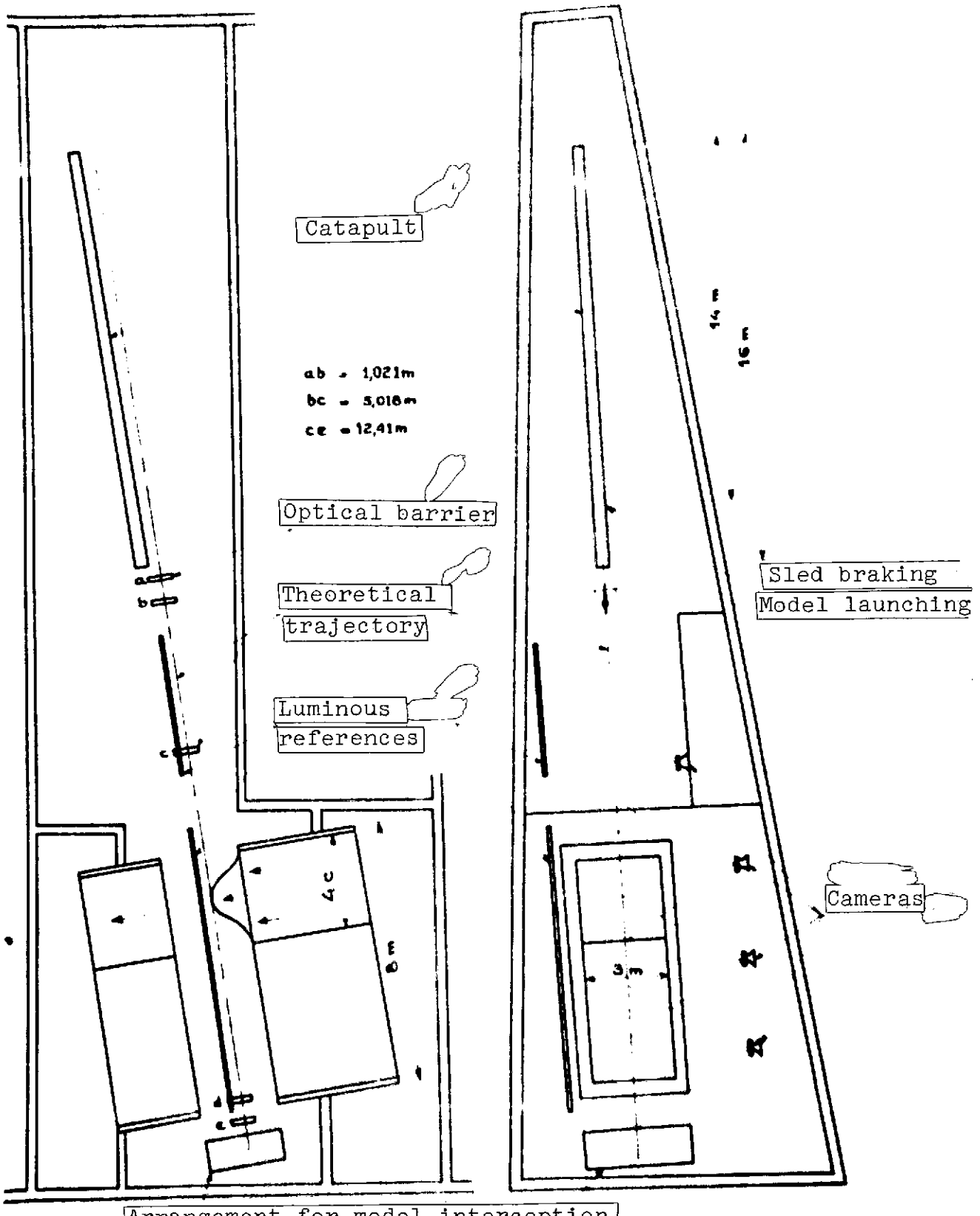


Types of Models

ORIGINE :

Test Station Schematic

Position of arrangements for geometric and velocity measurements



Arrangement for model interception

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CHAPTER II

Tests Conducted

In a general manner, three ranges of tests have been conducted during this program. /II-01

The most important, representing the plane profile of the wing without the influence of the forward fuselage and the propulsion system, corresponded to the calculated outline. We can group the tests with this simplified model into five categories:

— tests 36 - 37 - 38 for a mass of 2.52 kg and a moment of inertia 1463 cm^2 kg, and a 48% centering. These three tests differ by the vertical gust velocity modulus which is, respectively, 1.47, 2.90, and 1.95 meters per second.

The results are shown on Plate II.01, and they have been normalized to the same value $\mu = 2$, the gust modulus. We have shown by solid lines the average values of Z'' and θ''. Test 36 clearly gives higher values at the beginning of the penetration. Here the abscissae are in normalized time, that is, in numbers of reference chords traversed since the penetration of the apex in the gust whose duration is always 4 chords.

— tests 50 - 51 - 53 differ from the preceding ones by an increase in the moment of inertia to 1945 cm^2 kg for gust modulus of 1.91, 1.43, 2.89, and 2.44 meters per second. On the summary Plate II.02, we can see that if Z" is slightly changed, θ" is reduced by the increase in the moment of inerinertia.

— tests 64 - 65 - 66, where this time for the same centering and moment of inertia as the preceding group, the mass was increased to 2.952 kg. The results shown on Plate II.03 are quite dispersed in the penetration phase and show a smaller Z". /II-02

— tests 130 - 131 - 132 - 155 - 158 - 159 with a centering at 47%, all other conditions being analogous to tests 36 - 37 and 38.

The results are shown on Plate II.04, and show a slight increase in Z", as well as a second stronger peak of θ".

— tests 146 - 147 - 148, where this time the centering is at 48.5%. The results on Plate II.05 show a reduction of the second peak of θ".

The second series of tests concern a model equipped with its forward fuselage with a range 712 - 714 - 716 - 717, a larger mass of 3.119 kg, centered at 48%, a moment of inertia of 1742 cm^2 kg for 4 values of the gust speed modulus of 2.57, 3.15, 2.02, and 1.44 meters per second.

The results of this configuration are represented on Plate II.06. It seems that the first θ" peak is smaller.

Finally, the third series of tests studies a version of the complete aircraft with its forward fuselage, and the thrustor nacelles forming the test group 234 - 237 - 238 - 240 - 241 and 242. These are summarized on Plate II.07 for the same mass of 2.54 kg, a centering at 48%, and a moment of inertia

of 2041 cm^2 kg, and for 6 different values of gust speed modulus. We can see results that are, on the whole, fairly homogeneous; we also note a confirmation of a smaller θ" effect for stall* at the beginning of the penetration.

We can thus, in general, extract from this test series a number of conclusions.

First of all, the effect of penetration in the ascending gust produces a departure of the aircraft from stall conditions with a positive θ" followed by a larger negative peak, as we will see in the next chapter. These results confirm well the evolution of the generalized θ" coordinate found by computation.

On the other hand, despite a certain dispersion in the measurements, we can appreciate the effects of the mass, moment of inertia, and statistical margin parameters on the vertical and angular accelerations.

We have presented on Plate II.08 the maximum values of Z" and θ", positive and negative, as functions of the apparent incidence u/V of the gust for a range of tests 36 - 37 - 38, on the one hand, and 234 to 242, on the other. /II-03

The small dispersion causes a fairly large one on θ" in the first series, whereas the linearity is good in the second series.

We can also see that the effects of adding the thrustor nacelles are small.

The presence of a forward fuselage in relation to the wing can only lead to two conclusions:

*Translator's Note: Could also mean "nosing up".

1/ The pure effect of the forward fuselage is practically negligible (Z'' and θ'' being essentially zero at the time, $T = 0$ of the penetration of the wing apex in the gust).

2/ However, the effect of the forward point of the schematized airfoil is greater than that of the same section consisting of a cylindrical fuselage. This effect, particularly sensitive in pitch moment, produces a response in θ'' to stall at the beginning of the penetration that is smaller than for the complete aircraft.

This group of tests determines an average gust coefficient in the neighborhood of 0.9 at the center of gravity.

Plate II.01

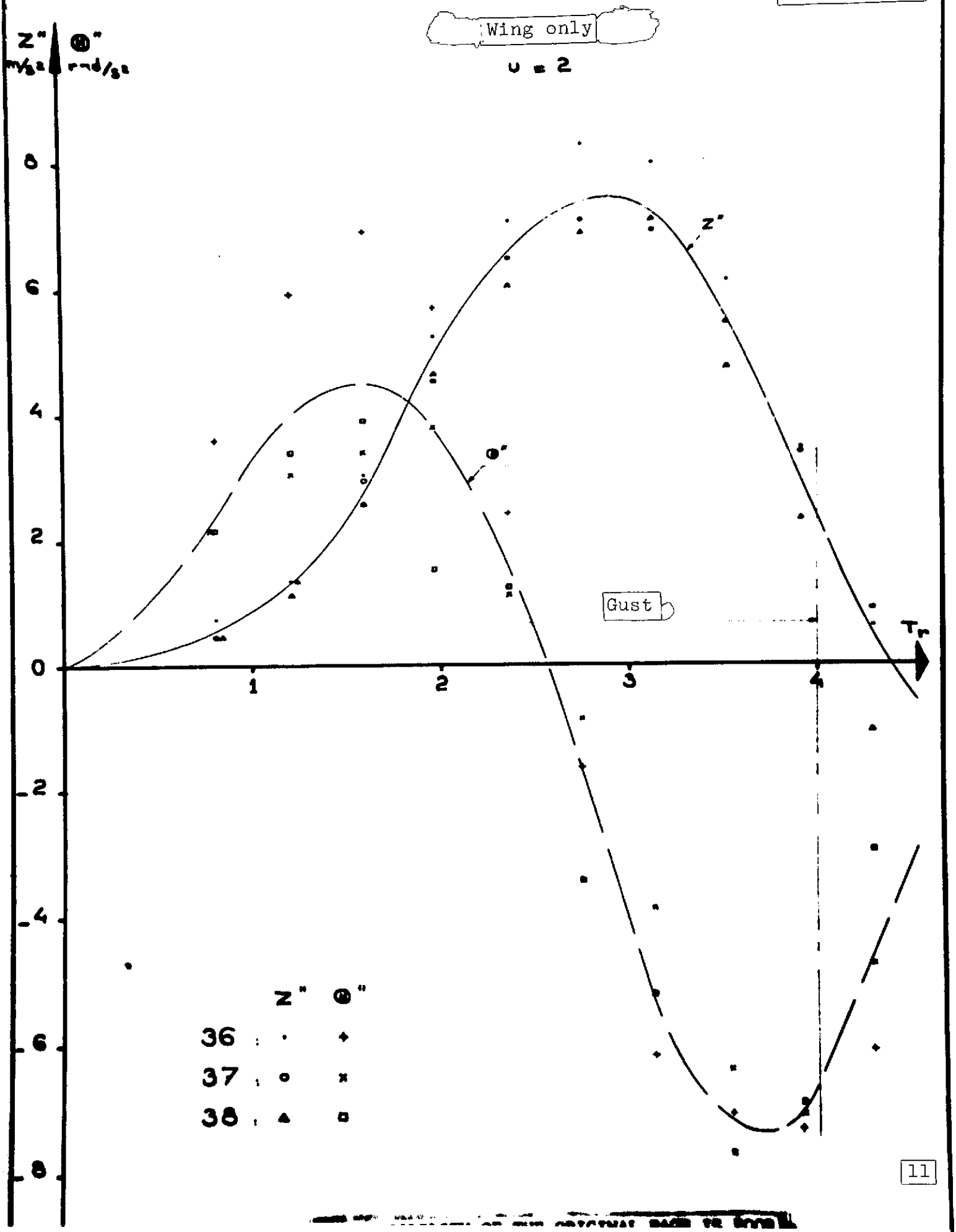

Plate II.02

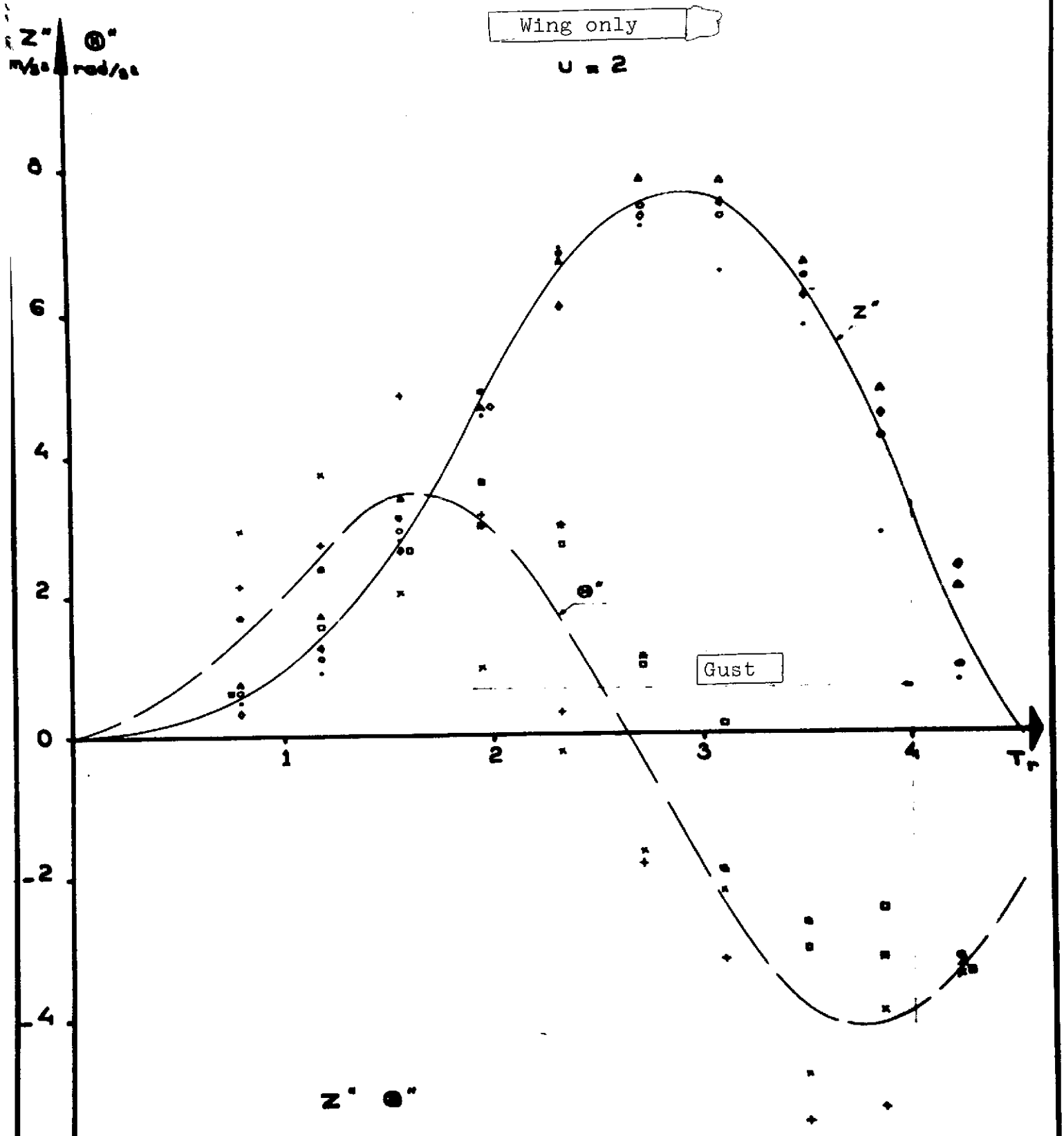

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Plate II.03

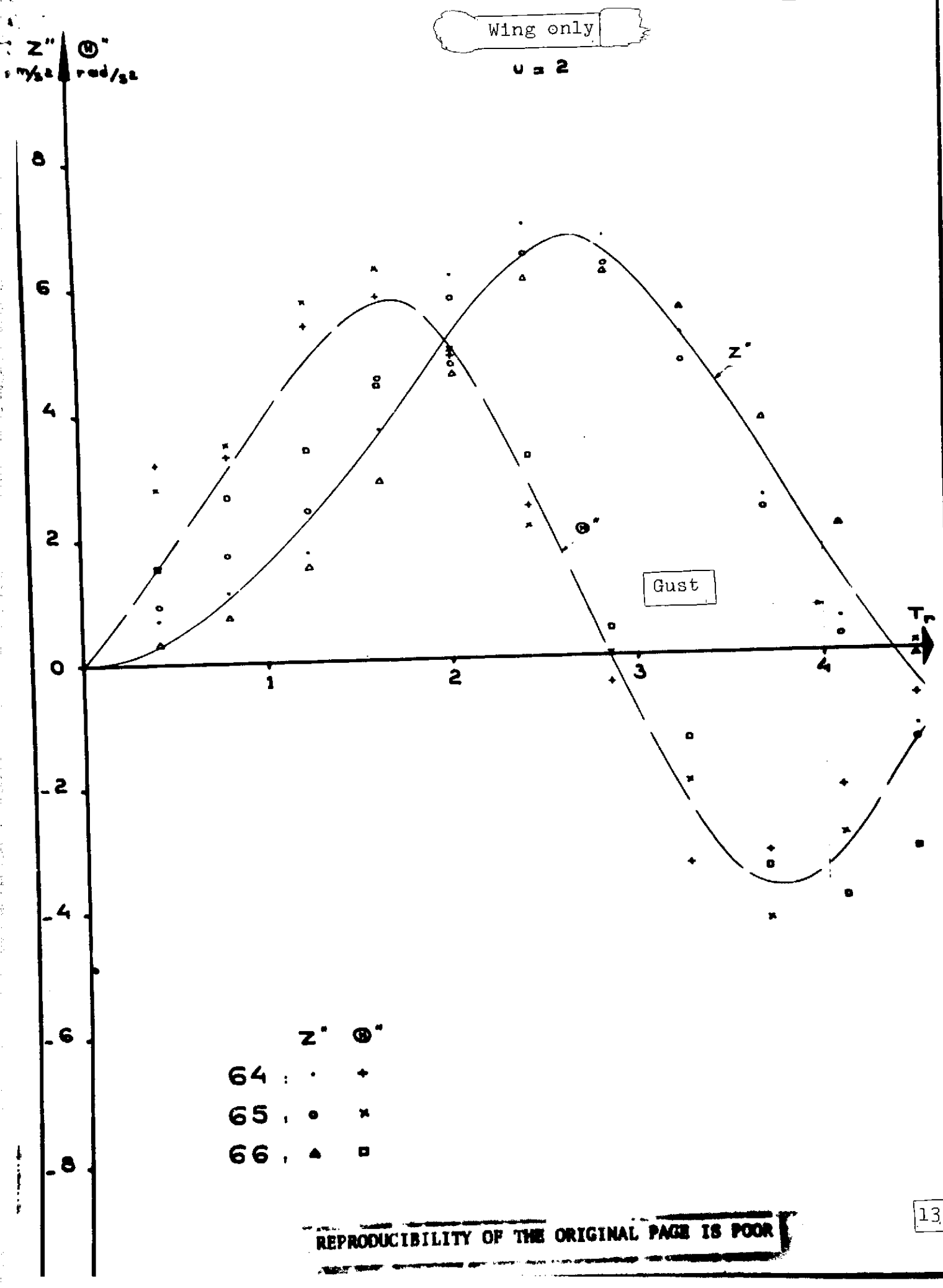

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Plate II.04.

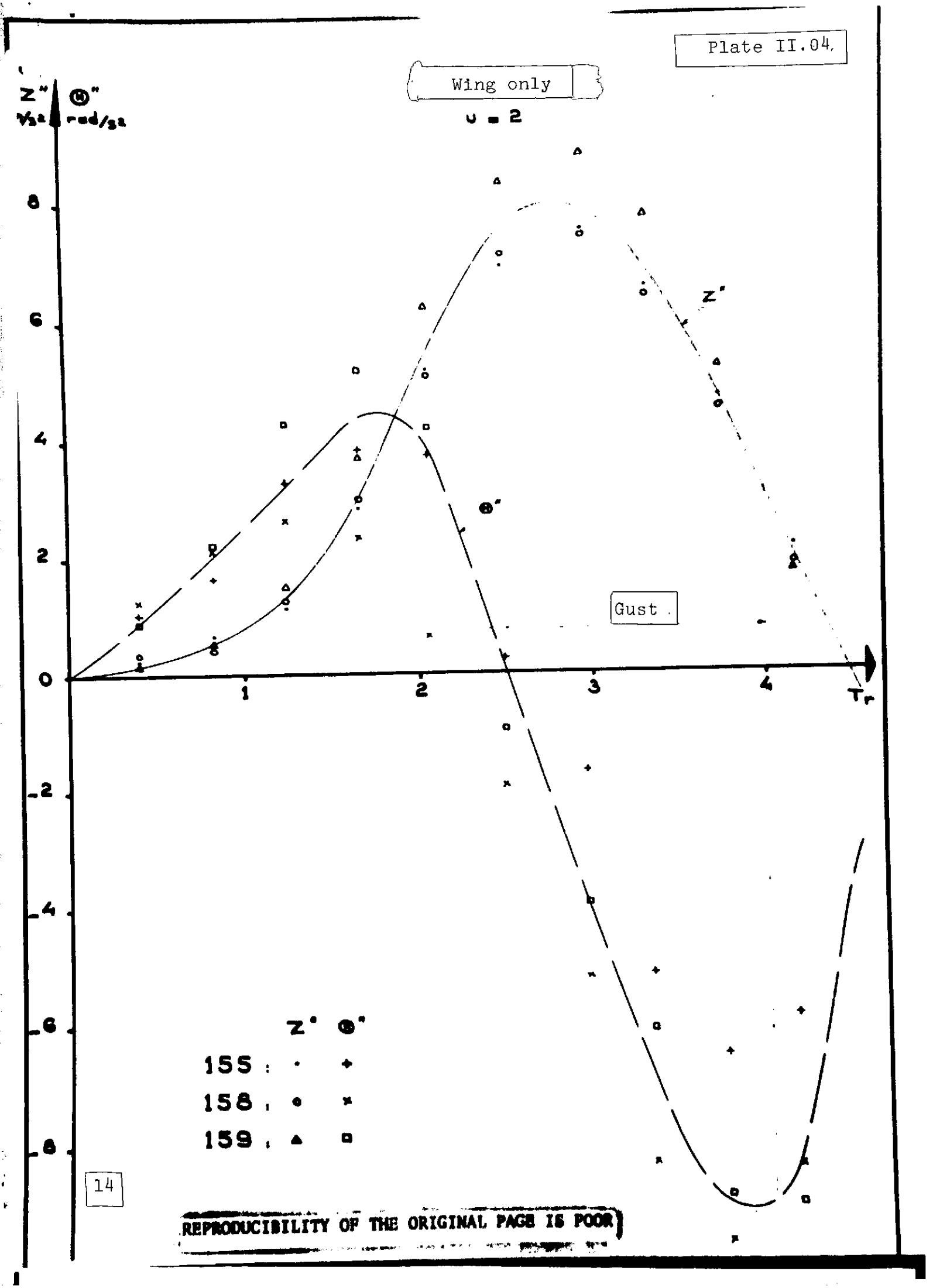

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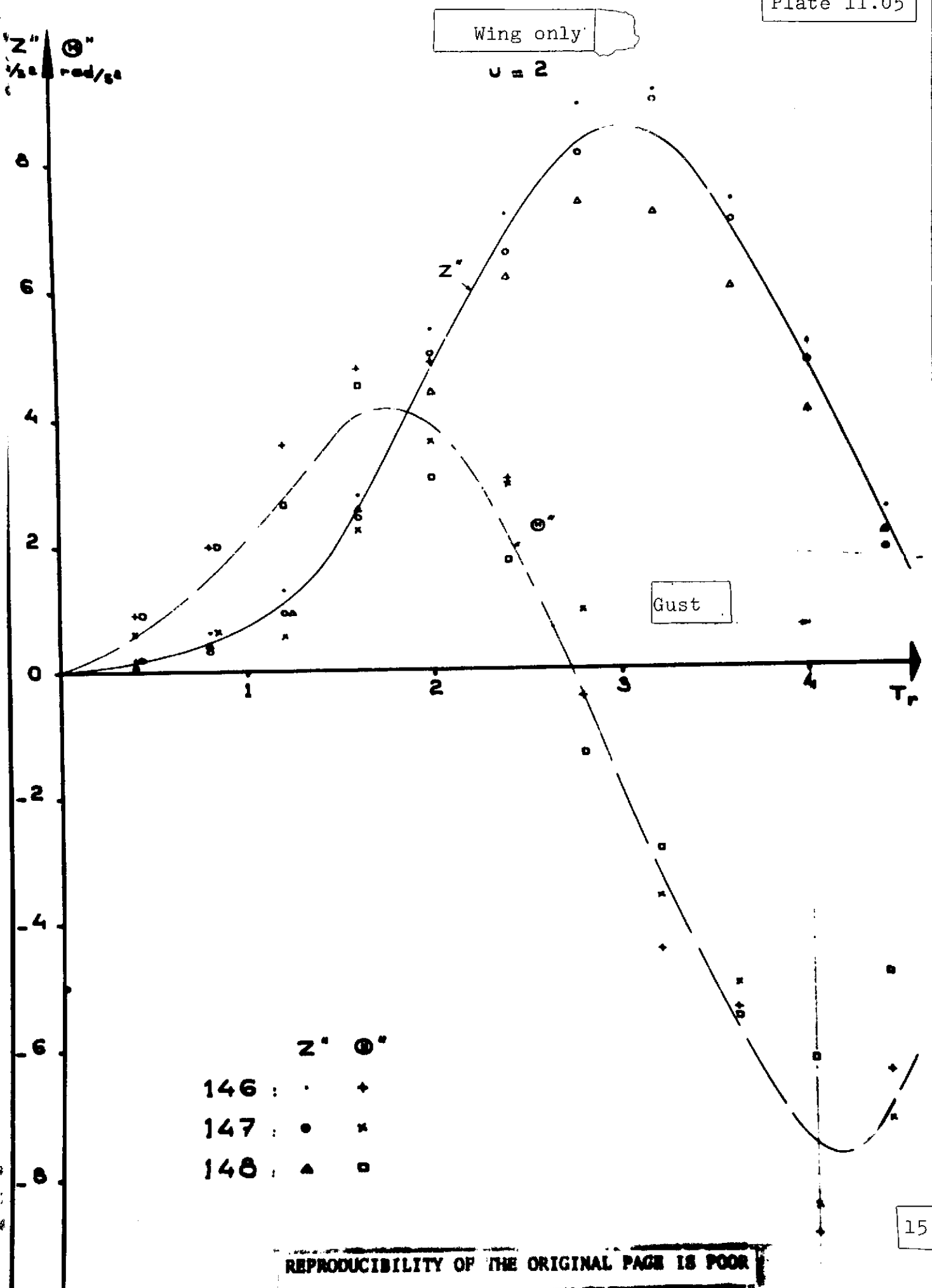
Plate II.05



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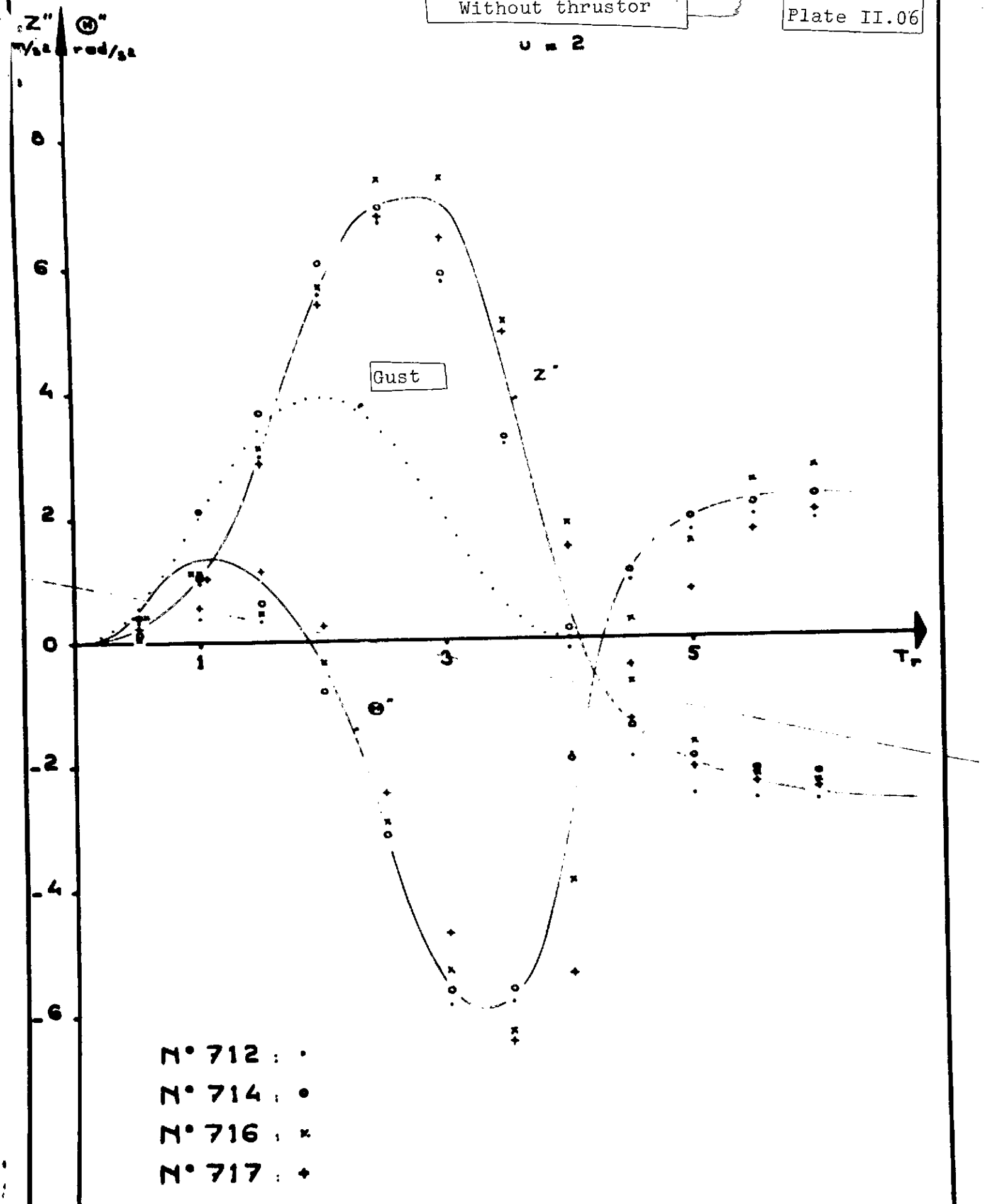
Without thrustor

Plate II.06

$\upsilon = 2$



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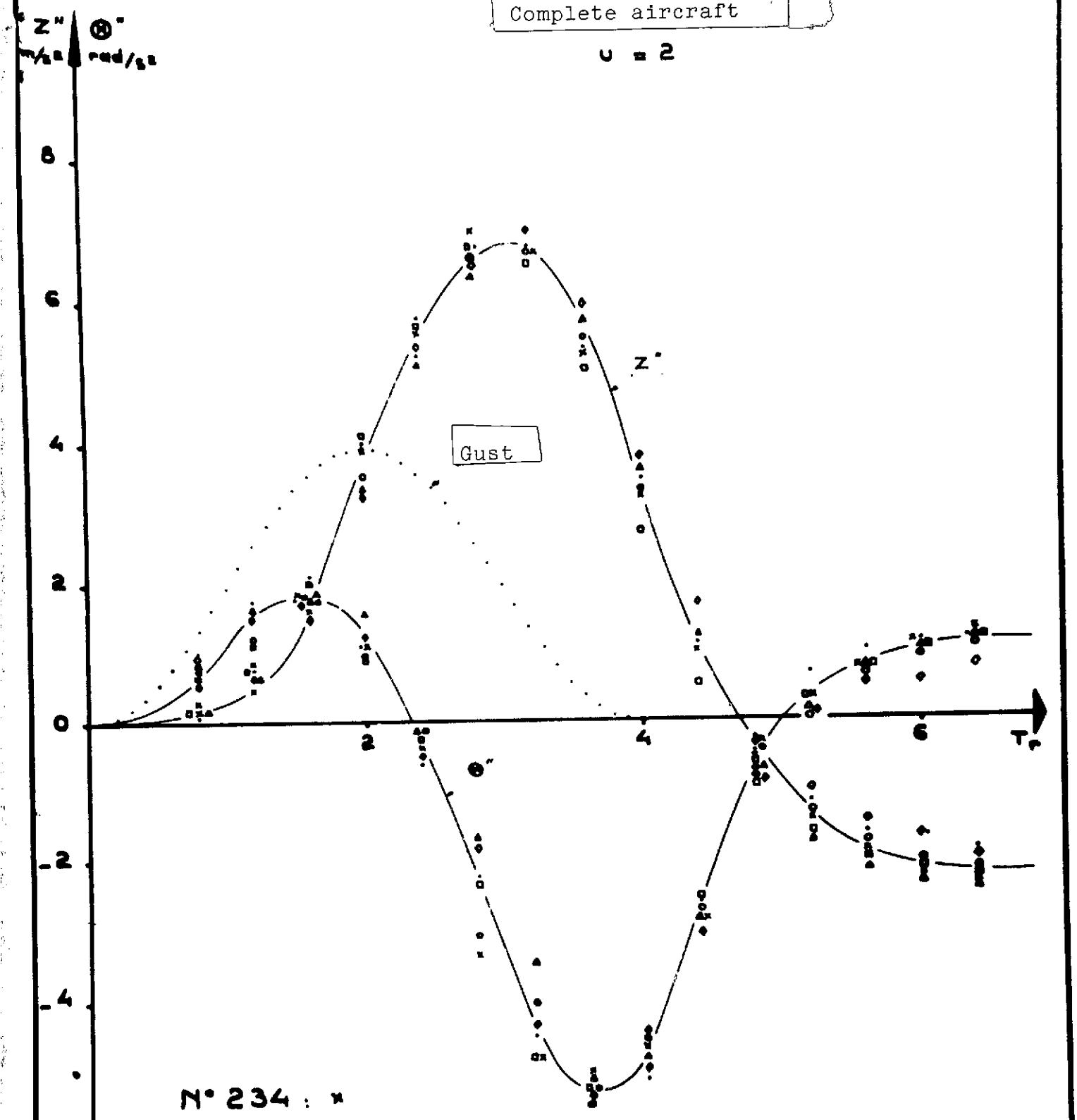
Complete aircraft

$\upsilon = 2$



N° 234 : ×
N° 237 : □
N° 238 : ·
N° 240 : ○
N° 241 : ◇
N° 242 : △

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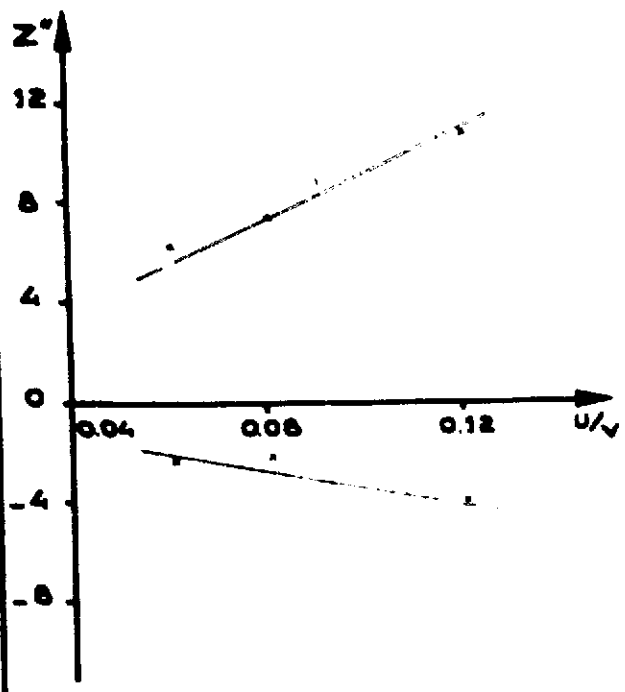
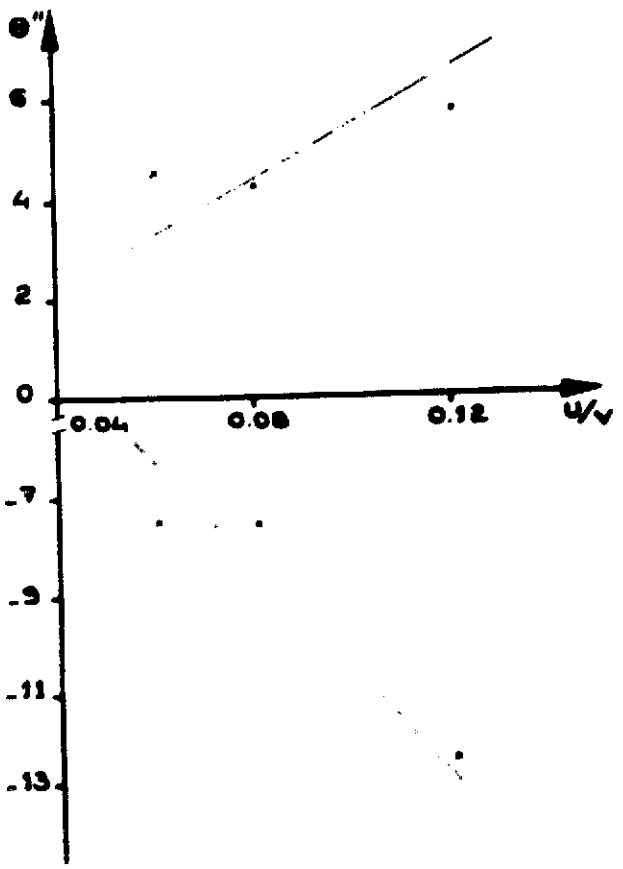
Wing only

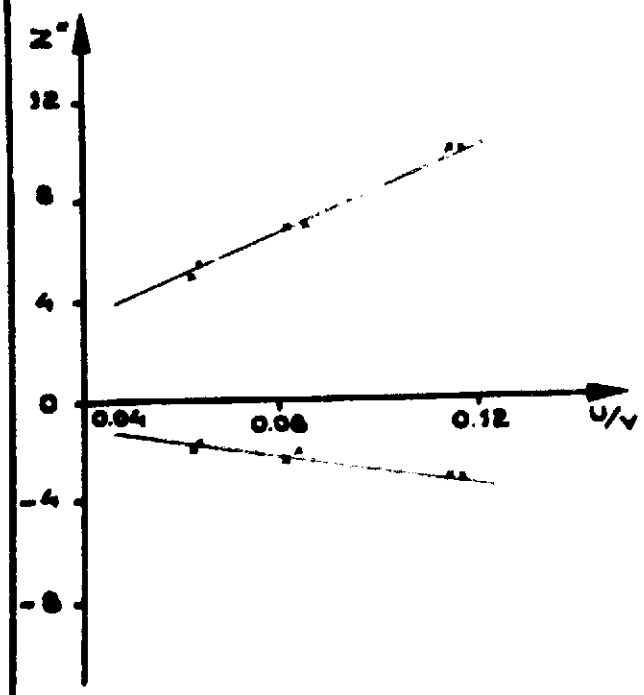
Series : 36 . 37 . 38

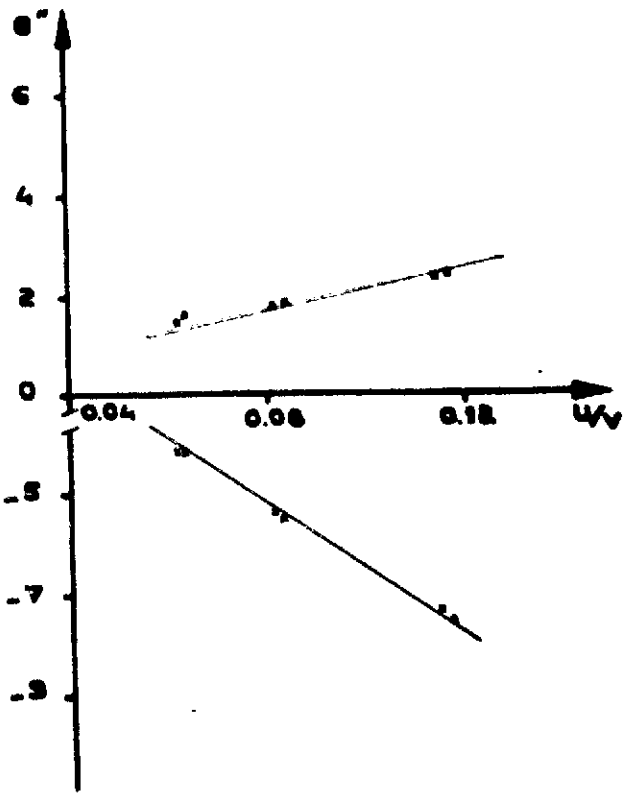




Complete aircraft

Series : 234 . 237 . 238 . 240 241 . 242





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CHAPTER III

Computations Made and Comparison with Tests

3.1. Principle of Computations Made

3.1.1. Preliminary studies

We recall that a certain amount of calculations had been conducted at the beginning of this study by trying to adopt the classic two-dimensional functions. /III-01

These functions, taken from the work of Mazelsky and Drischler, represented fairly poorly the establishment of forces and responses, particularly in that θ" was not very near the test results.

3.1.2. General equations of motion

The equations governing the vector {z} with the general components:

z, vertical translation of the center of gravity,
θ, position of the aircraft about its center of gravity;
[illegible], in the most general case, the generalized coordinate of mode i can be written:

$$\left[\frac{A}{\frac{1}{2}\rho V^2}\right]\{z''\} + \left[\frac{B}{V}\right]\{z'\} + [C]\{z\} = \left\{\int_0^t \frac{d}{d\tau}\left[\frac{w}{V}\left(1-\cos\frac{2\pi}{t_1}\tau\right)\right] \cdot C_{L_i}(t-\tau)\,d\tau\right\}$$

[A] generalized mass matrix;

[B] generalized damping matrix and matrix of the forces relative to the displacement velocities;

[C] generalized rigidity matrix and matrix of the forces relative to displacements;

C_{L_i} indicial function for the establishment of the generalized forces due to the gust.

In the particular case of the rigid aircraft presented here /III-02 with two degrees of freedom, translation and pitch, and with the hypothesis used in the calculations performed at the time of the tests, these matrices have the form:

$$[A] = \begin{bmatrix} \frac{m}{0,5\rho S} & \\ 0 & \frac{I}{0,5\rho S l} \end{bmatrix} \quad [B] = \begin{bmatrix} Cz_i & Cz_q l \\ Cm_i & Cm_q l \end{bmatrix} \quad [C] = \begin{bmatrix} 0 & Cz_i \\ 0 & Cm_i \end{bmatrix}$$

The quantities Cz_i and Cm_i have been determined starting from the permanent free flights of the model itself, and the values Cz_q and Cm_q have been computed.

The two indicial functions, relative to the bearing and pitch moment induced by the gust, have been obtained by a Fourier transform of the response in frequency of the generalized forces to a sinusoidal gust.

The generalized forces are calculated with the aid of the three-dimensional aerodynamic forces obtained by a solution of the integral equation relating pressure and displacement in the theory of lifting surfaces.

The wing is represented by 25 control points, 5 chords of 5 points each, whose distribution is imposed by the mean convergence of an approximation polynomial.

The apparent incidence of each of the control points is governed by the law $e^{j\omega\left(t - \frac{xi}{V}\right)}$, the origin of time being taken at the apex of the airfoil, and the term xi/V representing the time lag of each control point to the influence of the gust.

These indicial null functions at t = 0 must, in the limit of t = ∞, tend toward the stationary values Cz_i and Cm_i.

3.1.3. Determination of the aircraft response

The system of differential equations is integrated step by step by the Runge-Kutta method after a study of the convergence of the solution.

The Duhamel integration of the second member is evaluated by numerical integration for all the t_i's required for the integration of the system of differential equations. This, in general, is the part which takes the longest time in the calculations.

3.2. Results of Computations and Comparison with Tests

The case most particularly studied concerns the test group 36 - 37 - 38, where several adjustment hypotheses have been considered by causing the derivative Cm_i and its corresponding Cm_g to be varied, where C_{mg} is an indicial moment function. /III-03

We can see on Plate III.01 the results for Z" and θ" as a function of time compared to the mean of the tests:

— version 1. Direct calculations with the preceding hypothesis;

— version 3. Calculations carried out with an increase on the order of 50% in Cm_i;

— version 10. We have assumed, always with a correct function C_z or C_{Lg}, that the center is always situated at 2/3 of the chord affected by the penetration.

Other hypotheses have been applied in the calculations, but we will only cite three principal versions whose indicial functions are shown in Figure III.02.

On Plate III.01, we can see that the varible Z" is always correctly computed and varies little with the modifications of Cm_i and Cm_g. On the other hand, the variable θ" is very sensitive to variations in the derivatives of the pitch moment during the penetration in the gust. This variation is again pronounced by the model effect where the θ" are n times the aircraft θ", where n is the ratio of the dimensions in the similitude aircraft model.

In the same manner, we have represented in Plate III.03 the versions 1 and 10 of the calculations for the test group 50. Plate III.04 shows this for test group 60, and Plate III.05 — for group 130.

In a general manner, we can see that the variations of the Z" variable are well represented and that the variation in θ" is verified as to its form, its departure from stall, and there is a second oscillation with a stronger peak. But, in general, we find a first positive peak by calculation which is smaller than in the tests.

Plate III.01

Comparison: Tests - Computation

Wing only: Test 36 - 37 - 38

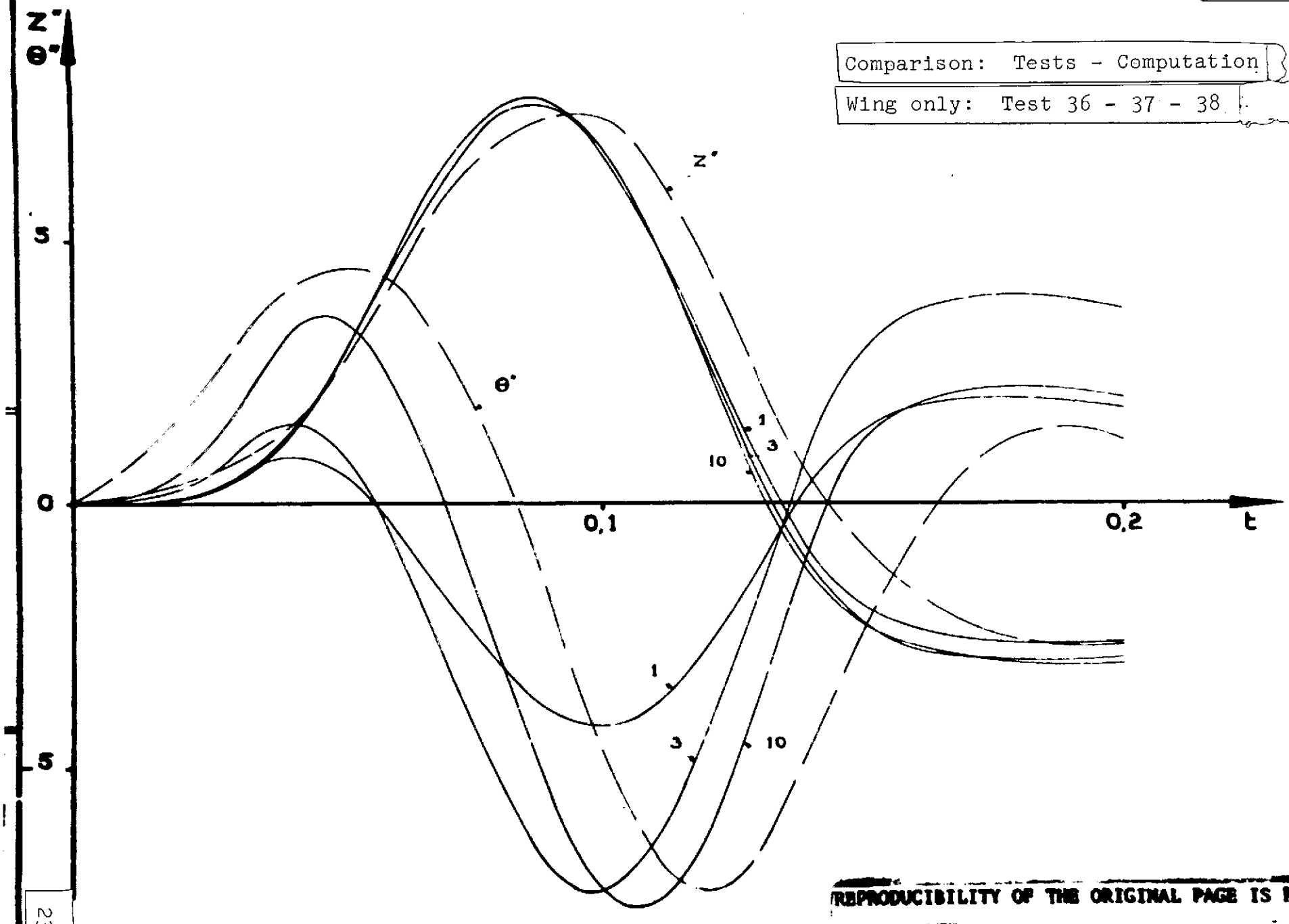

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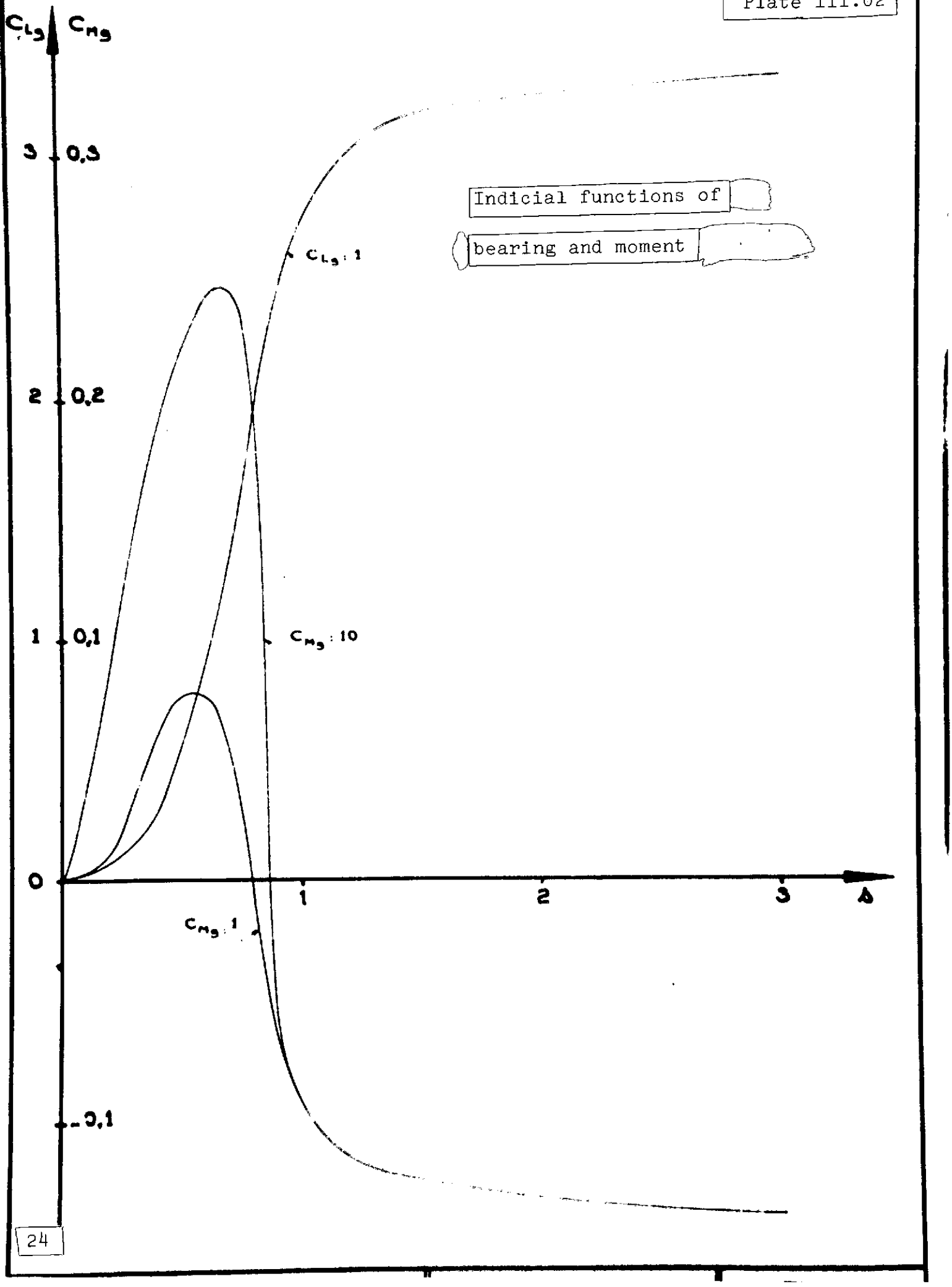
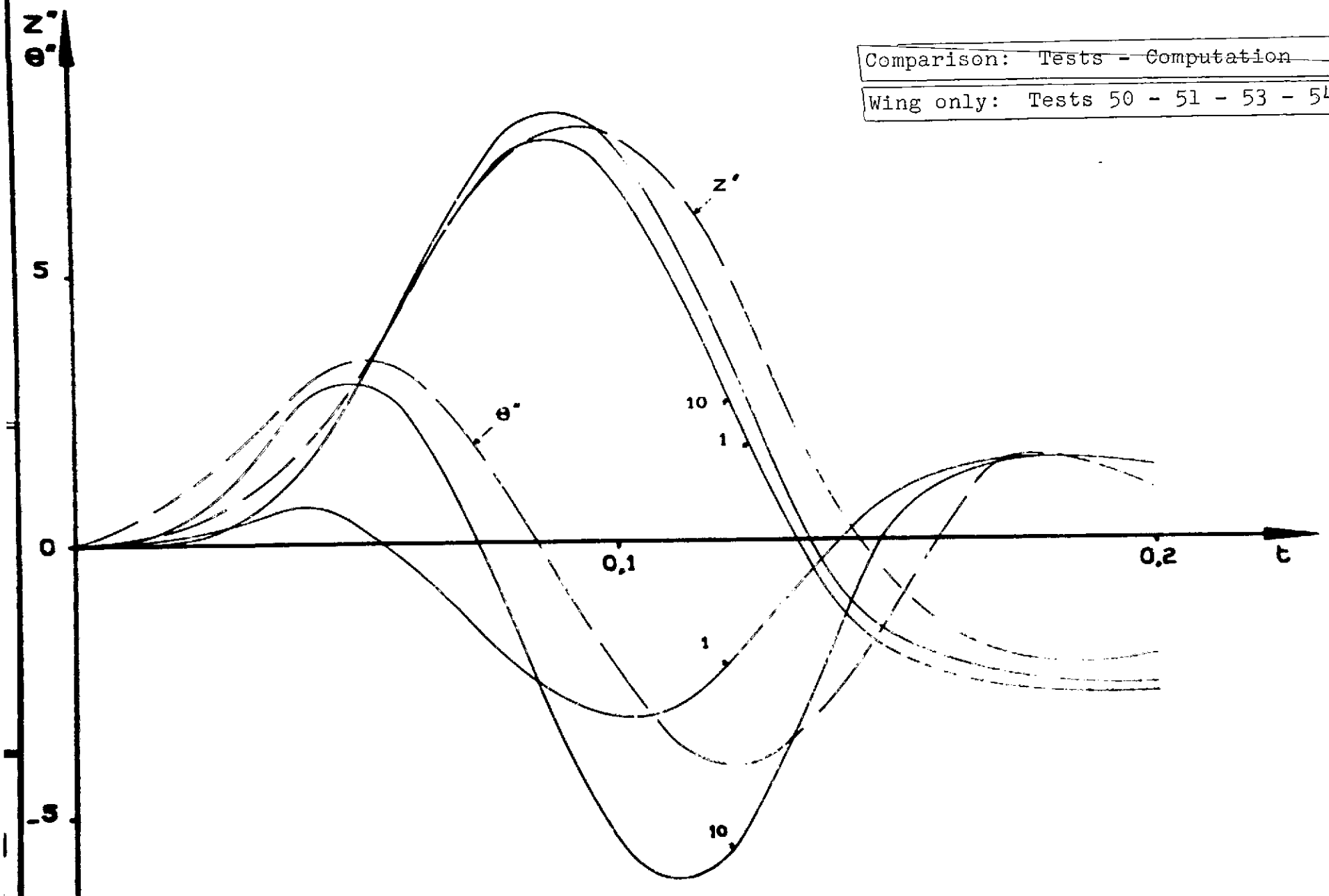
Plate III.02



Indicial functions of

bearing and moment

Plate III.03


Comparison: Tests - Computation
Wing only: Tests 50 - 51 - 53 - 54
Z°
θ°
5
0
-5
0,1
0,2
t
Z°
θ°
10
1
1
10

26

Plate III.04

Comparison: Tests - Computation

Wing only: Tests 64 - 65 - 66

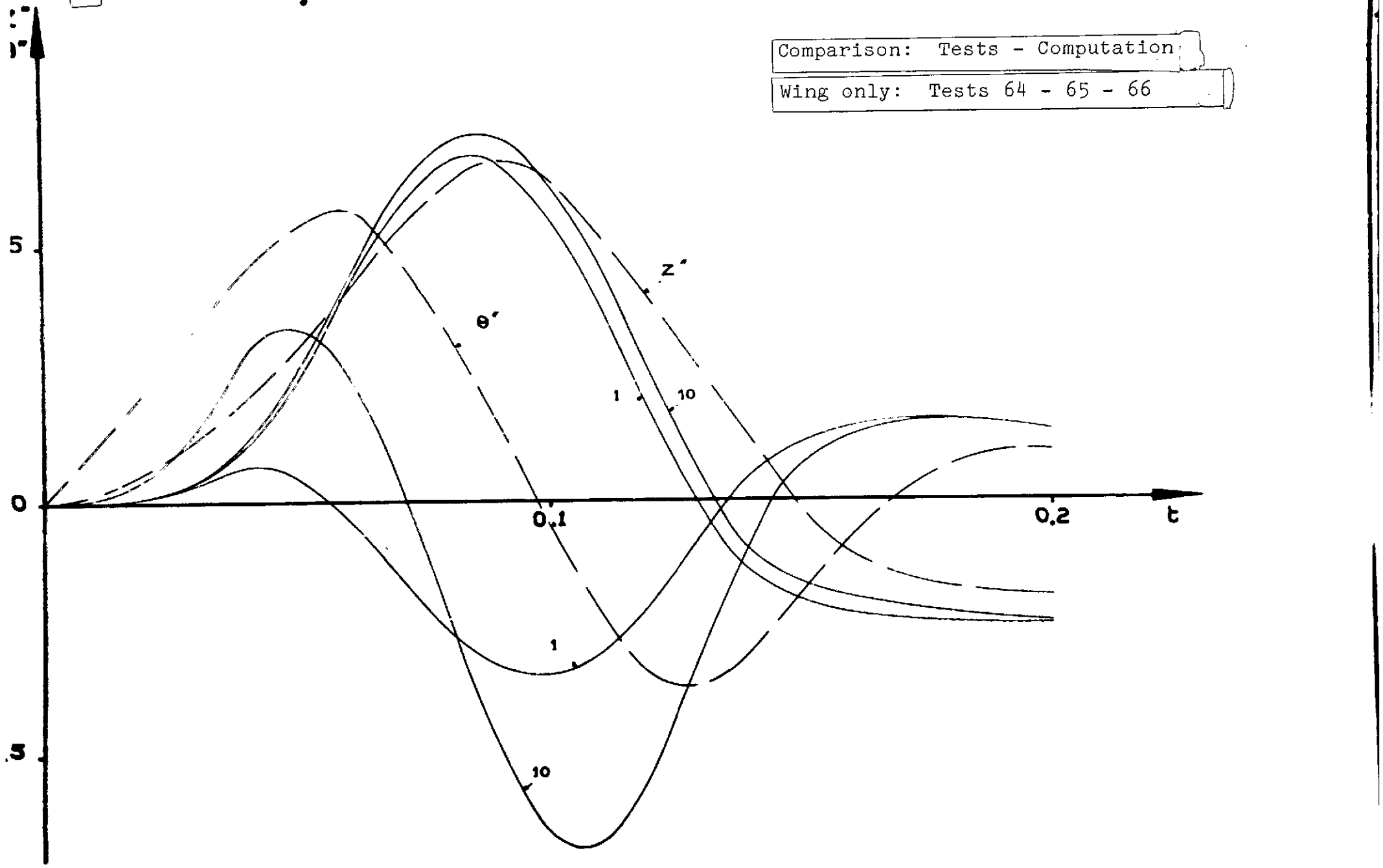


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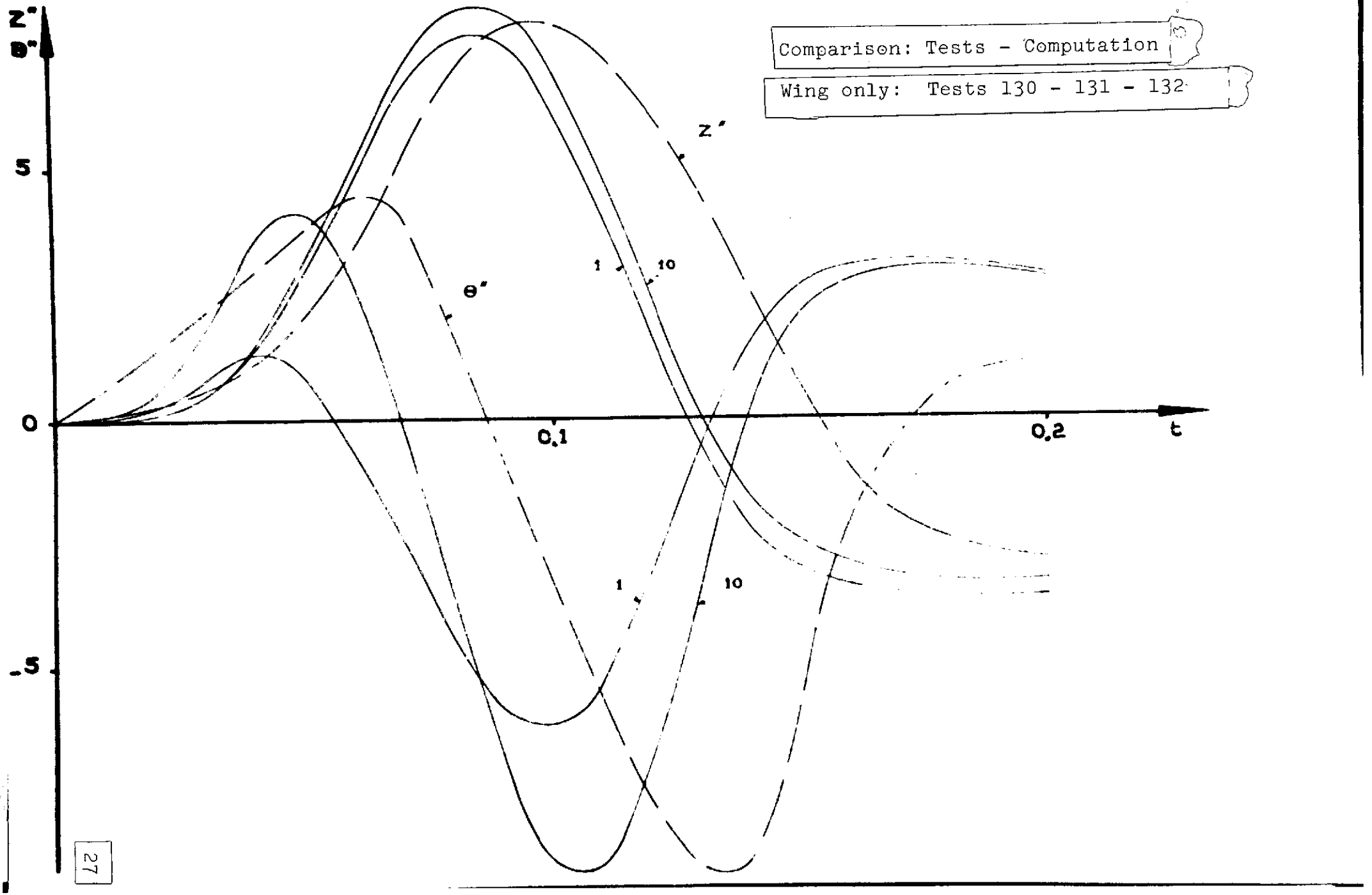
Plate III.05



Comparison: Tests - Computation

Wing only: Tests 130 - 131 - 132

CHAPTER IV

Remarks, Critique, and Improvements in the Calculations and in the Tests

We recall that these tests, conducted more than five years ago, /IV-01 included wind tunnel techniques, measuring techniques, and computational methods, and represent studies that were relatively new for an aircraft. For the new configuration, the classical two-dimensional theories are inapplicable.

4.1. Critique of the Tests

4.1.1. Free flight trajectories

The free flight of the model using a catapult was fairly delicate to stabilize, and well-established permanent flight conditions upon entry into the gust were fairly difficult to realize.

4.1.2. The measurements with accelerometers give results that are relatively accurate in the Z" variable, the average value weighted by two measurements. But the results of measurements give a poorer accuracy for the variable θ", obtained as a difference of two close values.

4.1.3. If direct stationary measurements Cz_i, Cm_i could be made using the model, the values Cz_q and Cm_q were not determined during the tests.

4.1.4. Taking account of the relatively low flight velocity, the apparent incidences of the profile are fairly high. But we have attempted to have linear conditions for the polar. Therefore, the possible catapulting velocities remained above the range used here.

4.2. Critique of the Computations

4.2.1. We note first that the two-dimensional calculations were not satisfactory. /IV-02

4.2.2. The quantities introduced in the first quasi-stationary term do not take into account the stationary terms induced by the complex potential.

4.2.3. The computation of the indicial functions, particularly of the moments, is fairly delicate.

The solution of the integral equation by the method of collocation could be improved by choosing a larger number of control points in the chord direction. The variations in the apparent incidence in the penetration effect would be better represented.

On the other hand, the results of the integral equation degrade at large reduced frequencies. A phenomenon of oscillation of the generalized computed forces in the frequency response can occur.

4.3. Improvements Applied to the Computations

4.3.1. Improvements applied to solution of the integral equation

The numerical evaluation of the kernel, the integration in the chord direction, and mainly in the span direction, becomes sensitive

with the presence of singularities. These were studied and considerably improved. From now on, we believe the tests of accuracy and convergence are satisfactory. On the other hand, the methods of solution have been diversified, and a network method of generalized doublets has been perfected which allows at the same time verifying the good convergence of the results and better representing the variations of apparent incidence.

4.3.2. Improvements in the calculation of the first term

The introduction of the terms of nonstationarity is performed in the following manner.

The local incidence at a point can be written as /IV-03

$$(\alpha_i + j\,k\,h_i)\,\eta_i = \alpha_i\,\eta_i + h_i\,\frac{\eta'_i}{V}$$

from which a corresponding generalized force is found:

$$F_{\eta_i \eta_j} = C_{\eta_i \eta_j}\,\eta_i + C'_{\eta_i \eta'_j}\,\frac{\eta'_i}{V}$$

The coefficients $C_{\eta_i \eta_j}$ and $C'_{\eta_i \eta'_j}$ are complex functions of the reduced frequency ω/V, and can be written:

$$C_{\eta_i \eta_j} = C'_{\eta_i \eta_j} + j\,\overset{''}{C}_{\eta_i \eta_j} = C'_{\eta_i \eta_j} + j\,\frac{\omega}{V}\,C''_{\eta_i \eta_j}$$

and also with $C_{\eta_i \eta'_j}$.

We can thus put $F_{\eta_i \eta_j}$ in the form:

$$F_{\eta_i \eta_j} = C'_{\eta_i \eta_j}\,\eta_i + (C''_{\eta_i \eta_j} + C'_{\eta_i \eta'_j})\,\frac{\eta'_i}{V} + C''_{\eta_i \eta'_j}\,\frac{\eta''_i}{V^2}$$

The computations of the terms C' and C"' are carried out around the resonant frequency of the modes. In the particular case of the rigid aircraft, these terms are estimated for a very low reduced frequency. Verification of the frequency response, in the form of

the modulus and the phase, have shown good agreement between the generalized forces calculated for pure nonstationary conditions, on the one hand, and the same forces computed from these coefficients which are made constants, on the other.

4.3.3. Qualifications for advanced geometry

For aircraft, such as the Airbus in particular, where the presence of a large fuselage can no longer be neglected, it becomes necessary to take account of the influence of the forward fuselage at the same time as the interaction phenomena between the airfoil and the fuselage.

4.4. Improvements to the Tests

The techniques of pitch and stability of the model have since been considerably improved, as well as the techniques of measurement and stationarity tests for the model. But this chapter will be treated in more detail in a communication following.